

The complete mitochondrial genome of *Orancistrocerus aterrimus aterrimus* and comparative analysis in the family Vespidae (Hymenoptera, Vespidae, Eumeninae)

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Abstract

To date, only one mitochondrial genome (mitogenome) in the Eumeninae has been reported in the world and this is the first report in China. The mitogenome of *O. a. aterrimus* is 17 972 bp long, and contains 38 genes, including 13 protein coding genes (PCGs), 23 tRNA genes, two rRNA genes, a long non-coding region (NCR), and a control region (CR). The mitogenome has 79.43% A + T content, its 13 PCGs use ATN as the initiation codon except for *cox1* using TTG, and nine genes used complete translation termination TAA and four genes have incomplete stop codon T (*cox2*, *cox3*, *nad4*, and *cytb*). Twenty-two of 23 tRNAs can form the typical cloverleaf secondary structure except for *trnS1*. The CR is 1 078 bp long with 84.69% A+T content, comprising 28 bp tandem repeat sequences and 13 bp T-strech. There are two gene rearrangements which are an extra *trnM2* located between *trnQ* and *nad2* and the *trnL2* in the upstream of *nad1*. Within all rearrangements of these mitogenomes reported in the family Vespidae, the translocation between *trnS1* and *trnE* genes only appears in Vespinae, and the translocation of *trnY* in Polistinae and Vespinae. The absent codons of 13 PCGs in Polistinae are more than those both in Vespinae and Eumeninae in the family Vespidae. The study reports the complete mitogenome of *O. a. aterrimus*, compares the characteristics and construct phylogenetic relationships of the mitogenomes in the family Vespidae.

Keywords

Eumeninae, mitochondrial genomes, *Orancistrocerus aterrimus aterrimus*, phylogenetic analysis, Vespidae

Introduction

Animal mitochondrial genomes (mitogenomes) have been widely used in studies of molecular evolution, population genetic structure, and phylogeny because of their stable gene content, rapid evolutionary rate, relatively conserved gene arrangement, maternal inheritance, and infrequent recombination (Wolstenholme 1992; Saccone et al. 1999; Oliveira et al. 2008; Li et al. 2017). The family Vespidae has more than 5000 known species worldwide, which are divided into six subfamilies, Euparagiinae, Masarinae, Eumeninae, Stenogastrinae, Polistinae, and Vespinae (Carpenter 1993), but their phylogenetics have not been settled. There have been ten mitogenomes sequences reported in the Vespidae (seven in the subfamily Vespinae, three in Polistinae, and one in Eumeninae) (Table 1). Among these six subfamilies, there are more than 3600 species in the subfamily Eumeninae worldwide, more than half of the known species of Vespidae. The species in Eumeninae, also known as potter wasps, are solitary, and mostly catch caterpillars as food for their next generation in the environment of farmlands, forests, and orchards, which can directly control caterpillar pests. To date, there is only one species (*Abispa ephippium*) with its mitogenome published (Cameron et al. 2008). *Orancistrocerus aterrimus aterrimus*, the species under study in this work, belongs to the Eumeninae, and is widely distributed in China (Jiangsu, Anhui, Fujian, Jiangxi, Hunan, Guangxi, Chongqing, Sichuan, Yunnan provinces), and Laos, Vietnam (Li 1985; Selis 2018).

In the present study, the complete mitogenome of *O. a. aterrimus* was sequenced using Illumina sequencing technique, and its characteristics analyzed, including gene rearrangements, nucleotide composition, codon usage, etc. More importantly, the phylogenetic relationships of 12 species of mitogenomes in Vespidae are constructed and discussed based on nucleotide sequences of 13 PCGs using both Maximum Likelihood (ML) and Bayesian Inference (BI) methods. The study updates phylogenetic research based on the mitogenomes, and provides basic information framework of mitogenomes in Vespidae for further research on the phylogenetic relationships of both genera and subfamilies in this family.

Materials and methods

Sample collection and DNA preparation

The specimens of *O. a. aterrimus* were collected from Yangshuo county of Guangxi province, preserved in the 100% ethanol, and stored at -20 °C. Total DNA of a single adult specimen was extracted from the muscle tissues using the DNeasy DNA Extraction Kit (QIAGEN) in accordance with the manufacturer's instructions. The concentration of genomic DNA in extraction product was assayed on a Qubit fluorometer using a dsDNA High-sensitivity Kit (Invitrogen).

Table 1. The information of Vespidae mitogenomes used in the phylogenetic analysis in the present study.

| Subfamily | Species | Migenome size (bp) | Gene number | GenBank Accession | Reference |
|------------------------------|--|--------------------|-------------|-------------------|-----------------------|
| Ingroup (Vespidae) | | | | | |
| Eumeninae | <i>Orancistrocerus aterrimus aterrimus</i> | 17972 | 38 | KY941926 | This study |
| Eumeninae | <i>Abispa ephippium</i> | 16953 | 41 | EU302588 | Cameron et al. (2008) |
| Polistinae | <i>Polistes jokahamae</i> | 16616 | 34 | KR052468 | Song et al. (2016) |
| Polistinae | <i>Polistes humilis synoecus</i> | 14741 | 34 | EU024653 | Cameron et al. (2008) |
| Polistinae | <i>Parapolybia crocea</i> | 16619 | 37 | KY679828 | Peng et al. (2017) |
| Vespinae | <i>Vespula germanica</i> | 16342 | 33 | KR703583 | Zhou et al. (2016) |
| Vespinae | <i>Vespa ducalis</i> | 15779 | 37 | KX950825 | Kim et al. (2017a) |
| Vespinae | <i>Vespa mandarinia</i> | 15902 | 37 | KR059904 | Chen et al. (2015) |
| Vespinae | <i>Vespa bicolor</i> | 16937 | 35 | KJ735511 | Wei et al. (2014) |
| Vespinae | <i>Vespa velutina nigrithorax</i> | 16475 | 37 | KY091645 | Kim et al. (2017b) |
| Vespinae | <i>Vespa orientalis</i> | 16101 | 37 | KY563657 | Nizar et al (2017) |
| Vespinae | <i>Dolichovespula panda</i> | 17137 | 37 | KY293679 | Fan et al (2017) |
| Outgroup (Formicidae) | | | | | |
| Formicinae | <i>Formica selysi</i> | 16752 | 37 | KP670862 | Yang et al. (2015) |

Mitogenomes sequencing and assembling

The Illumina TruSeq library was constructed from the gDNA with the average length of the inserted fragment of 480 bp. The library was sequenced on a full run of Illumina HiSeq 2500 with 500 cycles and paired-end sequencing (250 bp reads). High-quality reads were used in *de novo* assembly with IDBA-UD after removing adapters, unpaired, short and low quality reads (Peng et al. 2012). With IDBA-UD, these parameters have a similarity threshold of 98% and minimum and maximum k values of 80 and 240 bp, respectively. To identify the mitogenome assemblies from the pooled sequencing files, two different fragments of mtDNA (*cox1* and *rrnS*) were amplified as bait sequences by standard PCR reactions using primers designed with reference of Simon et al. (2006). Using BLASTN search against the reference of bait sequences, matching rate of 100% was confirmed as the mitogenome of *O. a. aterrimus*. The identical or near-identical overlapping terminal regions of mitogenome sequences were examined and circularized by Geneious (<http://www.geneious.com/>).

Sequence annotations and analysis

PCGs and rRNA genes were aligned with other published Vespidae insect mitogenomes by Clustal X (Thompson et al. 1997). The majority of the tRNA gene locations and secondary structures were identified by tRNAscan-SE Search Server v.1.21 (Lowe and Eddy 1997), and the remaining tRNA were identified in comparison with other known species of tRNAs in Vespidae (Cameron et al. 2008; Song et al. 2016). The CR

and the tandem repeat sequence were analyzed with Tandem Repeats Finder (<http://tandem.bu.edu/trf/trf.html>) (Benson 1999). Base composition and codon usage in all 12 mitogenomes of Vespidae were calculated by MEGA v 6. 0 (Tamura et al. 2013). In addition, the AT skew = $[A - T] / [A + T]$ and GC skew = $[G - C] / [G + C]$ were computed (Perna and Kocher 1995).

Phylogenetic analysis

Eleven known mitogenome sequences in the family Vespidae and the mitogenome sequence of *Formica selysi* (KP670862) in the family Formicidae were downloaded from GeneBank, and that of *O. a. aterrimus* was produced in the present study (Table 1). The phylogenetic tree of 12 mitogenomes sequences in the family Vespidae was constructed using ML and BI methods with MEGA 6.0 (Tamura et al. 2013) and MrBayes 3.1.1 (Huelsenbeck and Ronquist 2001), and the *Formica selysi* (KP670862) was used as outgroup. The nucleotide sequences of 13 PCGs were applied in the phylogenetic inference, and the best fitting substitution model was detected using Mrmodeltest 2.3 (Nylander 2004). The bootstrap values were calculated based on 1000 replications, and the confidence values of the topology is high.

Results and discussion

Genomic organization

The complete mitogenome of *O. a. aterrimus* is a double-strand of circular molecular DNA and 17,972 bp. It contains 38 genes: 13 PCGs, 23 tRNAs, two rRNAs, a control region (CR), and a long non-coding region (NCR) (Figure 1), of which 24 genes are situated in the majority strand (J-strand) and the other 14 genes are located in the minority strand (N-strand) (Table 2). An extra *trnM2* and a long NCR were found in the mitogenome. The gene *trnM2* is 67 bp and located in 2 142-2 208 between *trnQ* and *nad2*. The NCR is 1 946 bp long, located in 128-2 073 between *trnM1* and *trnQ*. With the exception of the NCR (1 946 bp), 14 intergenic spacers exist and sum to 174 bp, of which the longest spacer is 48 bp long, located between *nad4l* and *trnT*. In addition, a total of 24 bp overlaps was identified in 12 genes, with the overlap length of each gene ranging from 1 to 8 bp.

Gene rearrangements

The gene order of 13 PCGs and two rRNAs in *O. a. aterrimus* mitogenome is consistent with the putative hymenopteran ancestor: the sawfly *Perga condei* (Hymenoptera: Symphyta: Pergidae) (Castro and Dowton 2005). However, there are two rearrange-

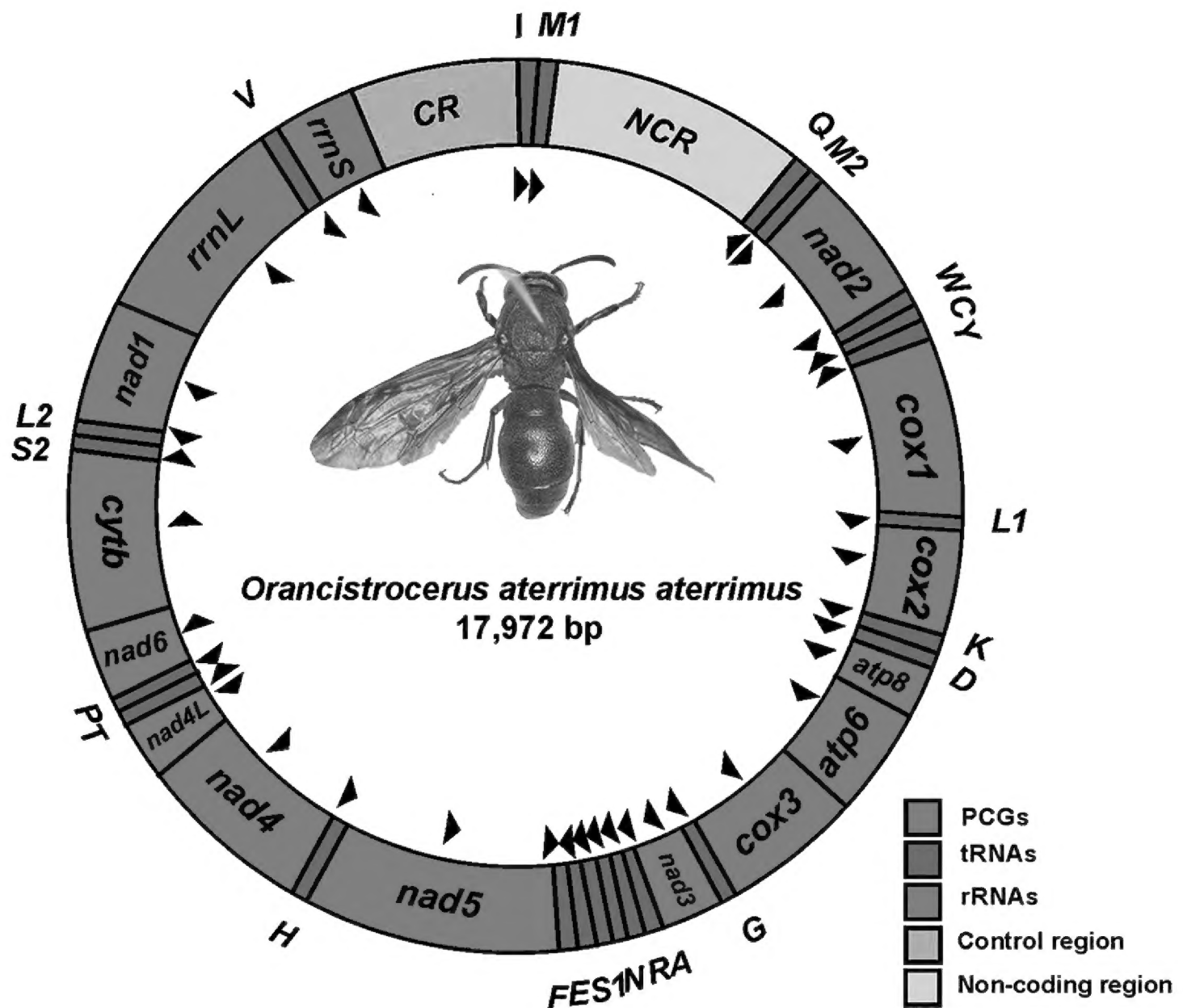


Figure 1. The mitochondrial genome of *O. a. aterrimus*. Arrows indicate the direction of genes. Abbreviations of the gene name are as follows: *nad1-4* and *nad4L* act as nicotinamide adenine dinucleotide hydrogen dehydrogenase subunits 1-6 and 4L; *cox1*, *cox2*, and *cox3* act as the cytochrome C oxidase subunits; *cytb* act as cytochrome b; *atp8* and *atp6* act as adenosine triphosphate synthase subunits 6 and 8; *rrnL* and *rrnS* act as large and small rRNA subunits; In addition, *CR* indicates control region and *NCR* indicates non-coding region.

ments of tRNAs in the mitogenome (Figure 2), namely, an extra *trnM2* and *trnL2* in the upstream of *nad1*, contributing to the novel gene order: *trnL2* - *nad1* - *rrnL* - *trnV* - *rrnS* - *CR* - *trnI* - *trnM1* - *trnQ* - *trnM2* - *nad2* (Figure 2). In the mitogenome of *Abispa ephippium*, another species in the subfamily Eumeninae, the gene order of rearrangements is *trnL2* - *trnM1* - *trnQ* - *trnM2* - *trnI*, *trnL1* - *trnL1* - *trnL1* - *trnL1* and *trnS2* - *nad1* (Figure 2) (Cameron et al. 2008). In the subfamily Polistinae, the translocation between *nad1* and *trnL1* is present in three reported species. In addition, the translocation of *trnY* in *Parapolybia crocea* occurs, *trnQ*, *trnM* and *trnY* genes are lost in *Polistes humilis* mitogenome, and in *Polistes jokahamae* mitogenome, not only *trnD* is in the upstream of *trnK* but also *trnI*, *trnQ* and *trnY* are missing (Figure 2) (Cameron et al. 2008; Song et al. 2016; Peng et al. 2017). In the subfamily Vespinae, except for the incomplete mitogenomes of *Vespula germanica* and *Vespa bicolor*, there is the

Table 2. Mitochondrial genome annotation of *O. a. aterrimus*.

| Gene | Direction | Location | Size (bp) | Anticodon | Codon | | Intergenic nucleotides |
|-------------------|-----------|-------------|-----------|-----------------|-------|------|------------------------|
| | | | | | Start | Stop | |
| <i>trnI</i> | F | 1–63 | 63 | 30–32 GAT | | | |
| <i>trnM1</i> | F | 63–127 | 65 | 93–95 CAT | | | -1 |
| non-coding region | | | | | | | 1946 |
| <i>trnQ</i> | R | 2074–2138 | 65 | 2108–2110 TTG | | | 0 |
| <i>trnM2</i> | F | 2142–2208 | 67 | 2173–2175 CAT | | | 3 |
| <i>nad2</i> | F | 2209–3234 | 1026 | | ATC | TAA | 0 |
| <i>trnW</i> | F | 3249–3315 | 67 | 3280–3282 TCA | | | 14 |
| <i>trnC</i> | R | 3308–3374 | 67 | 3342–3344 GCA | | | -8 |
| <i>trnY</i> | R | 3383–3447 | 65 | 3416–3418 GTA | | | 8 |
| <i>cox1</i> | F | 3446–4981 | 1536 | | TTG | TAA | -2 |
| <i>trnL1</i> | F | 5006–5073 | 68 | 5035–5037 TAA | | | 24 |
| <i>cox2</i> | F | 5074–5752 | 679 | | ATC | T- | 0 |
| <i>trnK</i> | F | 5753–5824 | 72 | 5785–5787 CTT | | | 0 |
| <i>trnD</i> | F | 5824–5893 | 70 | 5858–5860 GTC | | | -1 |
| <i>atp8</i> | F | 5894–6049 | 156 | | ATC | TAA | 0 |
| <i>atp6</i> | F | 6049–6720 | 672 | | ATG | TAA | -1 |
| <i>cox3</i> | F | 6742–7525 | 784 | | ATG | T- | 21 |
| <i>trnG</i> | F | 7526–7593 | 68 | 7556–7558 TCC | | | 0 |
| <i>nad3</i> | F | 7594–7947 | 354 | | ATT | TAA | 0 |
| <i>trnA</i> | F | 7947–8011 | 65 | 7977–7979 TGC | | | -1 |
| <i>trnR</i> | F | 8011–8074 | 64 | 8038–8040 TCG | | | -1 |
| <i>trnN</i> | F | 8078–8147 | 70 | 8108–8110 GTT | | | 3 |
| <i>trnS1</i> | F | 8147–8206 | 60 | 8168–8170TCT | | | -1 |
| <i>trnE</i> | F | 8214–8277 | 64 | 8244–8246 TTC | | | 7 |
| <i>trnF</i> | R | 8277–8342 | 66 | 8307–8309 GAA | | | -1 |
| <i>nad5</i> | R | 8344–10032 | 1689 | | ATT | TAA | 1 |
| <i>trnH</i> | R | 10033–10096 | 64 | 10065–10067 GTG | | | 0 |
| <i>nad4</i> | R | 10097–11402 | 1306 | | ATA | T- | 0 |
| <i>nad4l</i> | R | 11399–11677 | 279 | | ATT | TAA | -4 |
| <i>trnT</i> | F | 11726–11789 | 64 | 11756–11758 TGT | | | 48 |
| <i>trnP</i> | R | 11789–11858 | 70 | 11823–11825 TGG | | | -1 |
| <i>nad6</i> | F | 11860–12399 | 540 | | ATG | TAA | 1 |
| <i>cytb</i> | F | 12403–13534 | 1132 | | ATG | T- | 3 |
| <i>trnS2</i> | F | 13544–13612 | 69 | 13572–13574 TGA | | | 9 |
| <i>trnL2</i> | R | 13640–13707 | 68 | 13676–13678 TAG | | | 27 |
| <i>nad1</i> | R | 13708–14676 | 969 | | ATA | TAA | 0 |
| <i>rrnL</i> | R | 14682–16044 | 1363 | | | | 5 |
| <i>trnV</i> | R | 16043–16106 | 64 | 16074–16076 TAC | | | -2 |
| <i>rrnS</i> | R | 16107–16894 | 788 | | | | 0 |
| Control region | | 16895–17972 | 1078 | | | | 0 |

same rearrangements in other four reported species, such as the translocation of *trnY*, the translocation between *trnQ* and *trnM* genes, between *trnS1* and *trnE* genes, and between *nad1* and *trnL2*^(CUN) genes, respectively and *Dolichovespula panda* is different from other four species: the translocation between *trnS1* and *trnE* genes in exchange

| | | |
|--|-------------------------------------|---|
| Ancestral type <i>Perga condei</i> | I Q M nad2 W C Y cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Parapolybia crocea</i> | Y I Q M nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Polistes humilis</i> | I nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS |
| <i>Polistes jokahamae</i> | M nad2 W C cox1 L2 | cox2 D K atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespula germanica</i> | nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespa bicolor</i> | M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespa mandarinia</i> | Y I M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespa ducalis</i> | Y I M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespa orientalis</i> | Y I M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Vespa velutina nigrithorax</i> | Y I M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Dolichovespula panda</i> | Y I M Q nad2 W C cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Abispa ephippium</i> | M Q M I nad2 W C Y cox1 L2 L2 L2 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |
| <i>Orancistrocerus aterrimus aterrimus</i> | I M Q M nad2 W C Y cox1 L2 | cox2 K D atp8 atp6 cox3 nad3 A R N S1 E F nad5 H nad4 nad4 T P nad6 cytb S2 nad1 nad1 rml V rmlS CR |

Figure 2. Mitochondrial gene arrangement of 12 species of Vespidae. The red fonts indicate the rearrangement of the genes.

for shuffling of *trnN* and *trnE* (Figure 2) (Chen et al. 2016; Fan et al. 2017; Kim et al. 2017a; Kim et al. 2017b; Nizar et al. 2017). In general, the rearrangement frequency in Eumeninae is lower than those of both Vespinae and Polistinae. The rearrangement of *tRNAs* is a typical event in the mitogenomes of Hymenoptera (Dowton and Austin 1999; Dowton et al. 2009; Chen et al. 2016).

Nucleotide composition

To date, the nucleotide compositions of ten complete mitogenomes have been reported in the family Vespidae. In the subfamily Eumeninae, the overall A + T content of *O. a. aterrimus* and *Abispa ephippium* mitogenomes is 79.43% and 80.61%, respectively (Table 3). Among all Vespidae mitogenomes, there are no significant differences of the A + T content of Polistinae, i.e., *P. humilis* being 84.73%, *P. jokahamae* 83.41%, and *Parapolybia crocea* 82.94%, respectively. In the subfamily Vespinae, there are a little differences of the A + T content from *Vespa mandarinia* 79.39% to *Dolichovespula panda* being 84.61%. Generally speaking, the A + T content of Eumeninae is lower than those of both Vespinae and Polistinae. According to these different regions of *O. a. aterrimus* mitogenome, the A + T content of 13 PCGs is 78.27% near to *A. ephippium* (78.67%). In *tRNAs*, *rRNAs*, and CR, the A + T content is 83.41%, 84.29% and 84.69%, respectively. From the A + T content of all known Vespidae complete mitogenomes (Table 3), a universal feature is presumed that A + T content of *tRNAs* and *rRNAs* higher than that of PCGs.

Table 3. Nucleotide composition of different regions in all complete Vespidae mitogenomes.

| Species | Regions | Size(bp) | A% | T% | G% | C% | (A+T)% | AT-skew | GC-skew |
|-----------------------------------|----------------------|----------|-------|-------|-------|-------|--------|---------|---------|
| <i>Orancistrocerus aterrimus</i> | Whole genome | 17972 | 39.53 | 39.9 | 8.06 | 12.51 | 79.43 | -0.005 | -0.216 |
| | Protein coding genes | 11122 | 33.15 | 45.12 | 10.02 | 11.72 | 78.27 | -0.153 | -0.078 |
| | tRNA genes | 1525 | 42.69 | 40.72 | 9.25 | 7.34 | 83.41 | 0.024 | 0.115 |
| | rRNA genes | 2151 | 41.89 | 42.4 | 10.79 | 4.93 | 84.29 | -0.006 | 0.373 |
| | Control region | 1078 | 39.8 | 44.9 | 6.49 | 8.81 | 84.69 | -0.06 | -0.152 |
| <i>Abispa ephippium</i> | Whole genome | 16953 | 39.55 | 41.05 | 6.02 | 13.38 | 80.61 | -0.019 | -0.38 |
| | Protein coding genes | 11305 | 35.2 | 43.48 | 10.12 | 11.21 | 78.67 | -0.105 | -0.051 |
| | tRNA genes | 1787 | 44.66 | 38.84 | 8.95 | 7.55 | 83.49 | 0.07 | 0.085 |
| | rRNA genes | 2180 | 43.62 | 38.35 | 5.14 | 12.89 | 81.97 | 0.064 | 0.43 |
| | Control region | 308 | 43.83 | 46.1 | 1.3 | 8.77 | 89.94 | -0.025 | -0.742 |
| <i>Polistes jokahamae</i> | Whole genome | 16616 | 41.97 | 41.45 | 5.8 | 10.79 | 83.41 | 0.006 | -0.301 |
| | Protein coding genes | 10852 | 36.77 | 46.61 | 8.11 | 8.51 | 83.38 | -0.118 | -0.024 |
| | tRNA genes | 1318 | 44.76 | 42.64 | 6.98 | 5.61 | 87.4 | 0.024 | 0.108 |
| | rRNA genes | 2257 | 43.95 | 41.25 | 4.3 | 10.5 | 85.2 | 0.032 | 0.419 |
| | Control region | 1096 | 39.05 | 46.53 | 6.84 | 7.57 | 85.58 | -0.087 | -0.051 |
| <i>Polistes humilis</i> | Whole genome | 14741 | 43.09 | 41.65 | 5.32 | 9.95 | 84.73 | 0.017 | -0.303 |
| | Protein coding genes | 10852 | 36.77 | 46.61 | 8.11 | 8.51 | 83.38 | -0.118 | -0.024 |
| | tRNA genes | 1258 | 47.22 | 41.02 | 6.52 | 5.25 | 88.24 | 0.07 | 0.108 |
| | rRNA genes | 1932 | 43.27 | 43.22 | 9.16 | 4.35 | 86.49 | 0.001 | 0.356 |
| | Control region | * | * | * | * | * | * | * | * |
| <i>Parapolybia crocea</i> | Whole genome | 16619 | 43.39 | 39.55 | 5.91 | 11.15 | 82.94 | 0.046 | -0.307 |
| | Protein coding genes | 11022 | 35.48 | 45.16 | 9.54 | 9.82 | 80.65 | -0.12 | -0.015 |
| | tRNA genes | 1486 | 44.01 | 42.13 | 7.67 | 6.19 | 86.14 | 0.022 | 0.107 |
| | rRNA genes | 2176 | 40.3 | 45.96 | 9.38 | 4.37 | 86.26 | -0.066 | 0.365 |
| | Control region | 1316 | 42.25 | 46.05 | 5.17 | 6.53 | 88.3 | -0.043 | -0.117 |
| <i>Vespa ducalis</i> | Whole genome | 15779 | 40.32 | 39.8 | 5.8 | 14.08 | 80.12 | 0.006 | -0.417 |
| | Protein coding genes | 11159 | 34.32 | 43.46 | 10.36 | 11.86 | 77.78 | -0.118 | -0.067 |
| | tRNA genes | 1487 | 45.46 | 40.15 | 8.14 | 6.25 | 85.61 | 0.062 | 0.131 |
| | rRNA genes | 2299 | 44.58 | 39.58 | 11.44 | 4.39 | 84.17 | 0.059 | 0.445 |
| | Control region | 166 | 46.99 | 45.78 | 0 | 7.23 | 92.77 | 0.013 | -1 |
| <i>Vespa mandarinia</i> | Whole genome | 15902 | 38.88 | 40.51 | 6.07 | 14.53 | 79.39 | -0.021 | -0.41 |
| | Protein coding genes | 11119 | 33.73 | 43.37 | 10.56 | 12.35 | 77.09 | -0.125 | -0.078 |
| | tRNA genes | 1505 | 45.12 | 40.47 | 8.37 | 6.05 | 85.58 | 0.054 | 0.161 |
| | rRNA genes | 1569 | 43.91 | 39.64 | 12.11 | 4.33 | 83.56 | 0.051 | 0.473 |
| | Control region | 200 | 49 | 39.5 | 0.5 | 11 | 88.5 | 0.107 | -0.913 |
| <i>Vespa velutina nigrithorax</i> | Whole genome | 16475 | 40.3 | 41.44 | 5.43 | 12.83 | 81.74 | -0.014 | -0.406 |
| | Protein coding genes | 11197 | 34.99 | 44.75 | 9.42 | 10.83 | 79.74 | -0.122 | -0.07 |
| | tRNA genes | 1514 | 44.58 | 41.35 | 8.12 | 5.94 | 85.93 | 0.038 | 0.155 |
| | rRNA genes | 2319 | 45.11 | 40.06 | 10.52 | 4.31 | 85.17 | 0.059 | 0.419 |
| | Control region | 132 | 50.76 | 41.67 | 0 | 7.58 | 92.42 | 0.098 | -1 |
| <i>Vespa orientalis</i> | Whole genome | 16101 | 40.65 | 40.3 | 5.86 | 13.19 | 80.95 | 0.004 | -0.384 |
| | Protein coding genes | 10653 | 34.5 | 44.08 | 9.74 | 11.68 | 78.58 | -0.122 | -0.09 |
| | tRNA genes | 1481 | 45.51 | 40.51 | 7.97 | 6.01 | 86.02 | 0.058 | 0.14 |
| | rRNA genes | 2079 | 43.67 | 39.15 | 11.5 | 5.68 | 82.83 | 0.055 | 0.339 |
| | Control region | 60 | 48.33 | 41.67 | 8.33 | 1.67 | 90 | 0.074 | 0.667 |
| <i>Dolichovespula panda</i> | Whole genome | 17136 | 42.8 | 41.81 | 5.39 | 10 | 84.61 | 0.012 | -0.3 |
| | Protein coding genes | 11276 | 35.82 | 46.78 | 8.78 | 8.62 | 82.6 | -0.133 | 0.009 |
| | tRNA genes | 1506 | 45.88 | 40.44 | 7.9 | 5.78 | 86.32 | 0.063 | 0.155 |
| | rRNA genes | 2126 | 43.7 | 40.87 | 10.68 | 4.75 | 84.57 | 0.033 | 0.384 |
| | Control region | 586 | 67.24 | 32.42 | 0 | 0.34 | 99.66 | 0.349 | -1 |

* *P. humilis* (EU024653), not sequenced for the control region

Two other parameters, AT-skew and GC-skew, have been widely used to measure the nucleotide compositional behaviors of mitogenome in addition to the A + T content (Enrico et al. 2011). The AT skew of *O. a. aterrimus* mitogenome is -0.005 near to 0, and the GC skew (-0.216) is negative. The base composition bias plays an important role in researching the mechanism of replication and transcription of mitogenomes (Wei et al. 2010).

Among the PCGs of 12 Vespidae species (containing two incomplete mitogenomes), the A + T content of *cox1* is the lowest in 13 PCGs, ranging from 70.18% (*Vespa mandarinia*) to 75.29% (*P. humilis*) (Figure 3). The A + T content of *atp8*, *nad2*, and *nad4L* is highest (Figure 3). This result ascertains *cox1* is conserved relatively again, which is the reason for former abundant phylogenetic analysis in other insects (Rivera and Currie 2009; Santos et al. 2015). In addition, it is a common phenomenon that T content is more than A, and C content is slightly more than G (Figure 3).

Protein coding genes

In the 13 PCGs of the *O. a. aterrimus* mitogenome, nine PCGs are encoded in the J-strand, and the other four PCGs are located in the N-strand. The total length of PCGs is 11 122 bp. All PCGs use the conventional start codons ATN except for *cox1* using TTG which was also employed as the initiation codon in other insects (Sheffield et al. 2008; Li et al. 2012a). The termination codons of nine PCGs in *O. a. aterrimus* mitogenome use complete TAA (*nad2*, *cox1*, *atp8*, *atp6*, *nad3*, *nad5*, *nad4L*, *nad6* and *nad1*), and other four genes have incomplete stop codons T (*cox2*, *cox3*, *nad4* and *cytb*). In general, the termination codons of insect mitogenomes PCGs were the TAA or incomplete T (Ojala et al. 1981; Li et al. 2012a).

There is a total of 3697 codons in *O. a. aterrimus* mitogenome, excluding termination codons, which is within the range of the common insect mitogenomes codon number (3585-3746) (Cha et al. 2007). According to the relative synonymous codon usage (RSCU), all of these 12 Vespidae species frequently used UUU, UUA, AUU and AUA (Figure 4), leading to the high A + T content in the PCGs of the family Vespidae mitogenomes. CUG is absent in *O. a. aterrimus* mitogenome and CGC and AGC are absent in *A. ephippium*. Some codons are also lacking in other species of Vespidae. For example, CGC and AGC in *Vespa orientalis*, CUG, GCG, CGC in *V. bicolor* and CCG, ACC, ACG, GCG, UGC, and CGC in *Dolichovespula panda* are absent, respectively. There are several codons missing in *Polistes jokahamae*, namely, CUG, GUC, ACG, GCG, CGC, CGG, AGC; and CUG, GUC, GCG, CGC, and GGC are also lacked in *P. humilis* (Figure 4). Thus, the amount of absent codons in Vespinae and Polistinae is more than in Eumeninae.

Transfer RNA and ribosomal RNA genes

There are 23 tRNAs found in *O. a. aterrimus* mitogenome and their lengths range from 60 bp (*trnS1*) to 72 bp (*trnK*) including an extra *trnM2*, whereas usually there

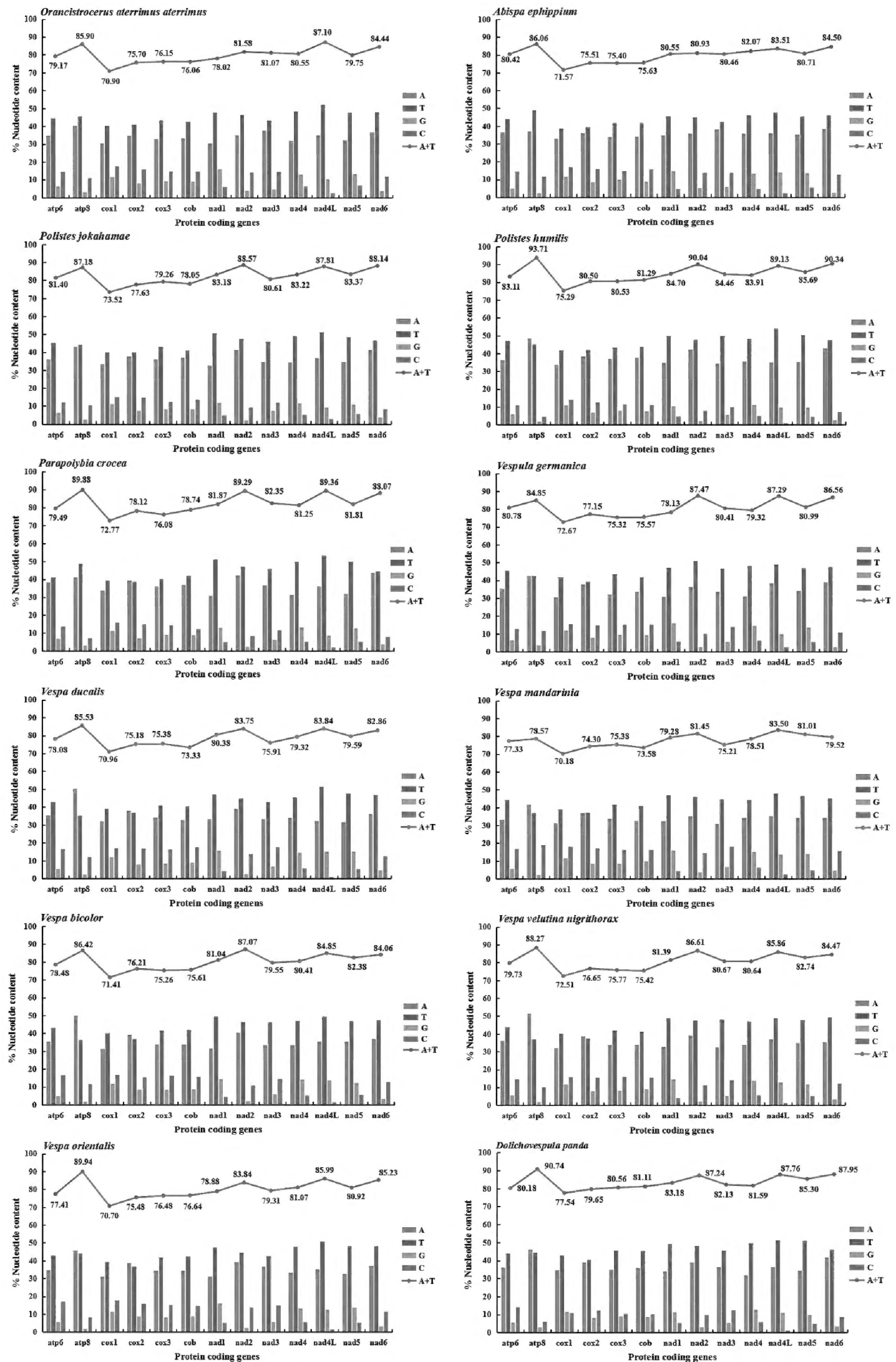
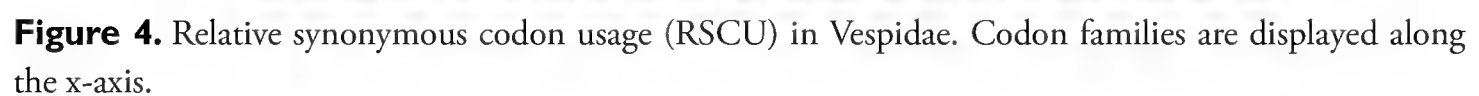


Figure 3. Nucleotide composition of all 13 PCGs of eleven species of Vespidae.



are 22 tRNAs in other insects (Boore 1999; Chen et al. 2015). Among 23 anticodons of these tRNAs, 21 are coincident with the majority of insects mitogenomes (Lee et al. 2008; Hua et al. 2016), but *trnI* and *trnS1* change from CCT to GAT, and GCT to TCT, respectively. Except for *trnS1*, the other 22 tRNAs have the capability of folding into typical clover-leaf secondary structures. The secondary structure of *trnS1* lacks the dihydrouridine DHU arm and reduces its shape to a simple loop (Figure 5), which is a common phenomenon in metazoan mitogenomes (Wolstenholme 1992; Li et al. 2012b). There are 20 mismatches in 13 tRNAs, including 18 unmatched GU base pairs, an unmatched AG, and an unmatched UU (Figure 5).

The length of *rrnL* is 1 363 bp long, located between *nad1* and *trnV*, and *rrnS* 788 bp long in minority strand between *trnV* and CR. The A + T content of two genes is 84.29% (*rrnL* and *rrnS*) (Table 3).

A control region and a non-coding region

The CR plays an important role in regulating of replication and transcription of mitogenomes (Taanman 1999; Saito et al. 2005). The CR of *O. a. aterrimus* mitogenome is 1078 bp long, located between *rrnS* and *trnI*. The A + T content of this region (84.69%) is higher than other region of the *O. a. aterrimus* mitogenome. There is a tandem repeat model of 28 bp (TATTCCATTTAAGTTCGTAAAACTAAT) which occurs more than eight times in the *O. a. aterrimus* mitogenome. Tandem repeat structures in the CR are different in different species (Peng et al. 2017). There is also a poly-T stretch of 13 bp, which may be as recognition site for the initiation of replication in the mitogenomes (Andrews et al. 1999). In the *O. a. aterrimus* mitogenome, a NCR is situated in position 128 - 2 073 (1 946 bp) between *trnM1* and *trnQ*, which is reported in most insect mitogenomes (Saito et al. 2005; Cameron et al. 2008; Jiang et al. 2016). The A + T content of NCR is 73.69%, among which there is 97 bp (close to *trnQ* gene) with obviously high A + T content 90.72%. In addition, two tandem repetitive sequences are found in the NCR, which repeated 17 and 18 times, respectively.

Phylogenetic relationships

The best fitting model GTR + G + I was selected for ML analysis. The phylogeny of mitogenomes in Vespidae was constructed based on the nucleotide sequences of 13 PCGs of 13 species using ML and BI methods (Figure 6). The phylogenetic relationships between 12 species in the family Vespidae are (((((*Vespa bicolor* + *Vespa velutina nigrithorax*) + *Vespa orientalis*) + (*Vespa mandarinia* + *Vespa ducalis*)) + *Vespula germanica* + *Dolichovespula panda*) + (*Parapolybia crocea* + (*Polistes humilis synoecus* + *Polistes jokahamae*))) + (*Orancistrocerus aterrimus aterrimus* + *Abispa ephippium*) (Figure 6). *O. a. aterrimus* and *A. ephippium* belong to the subfamily Eumeninae, which is concordant with morphological classification. In the present

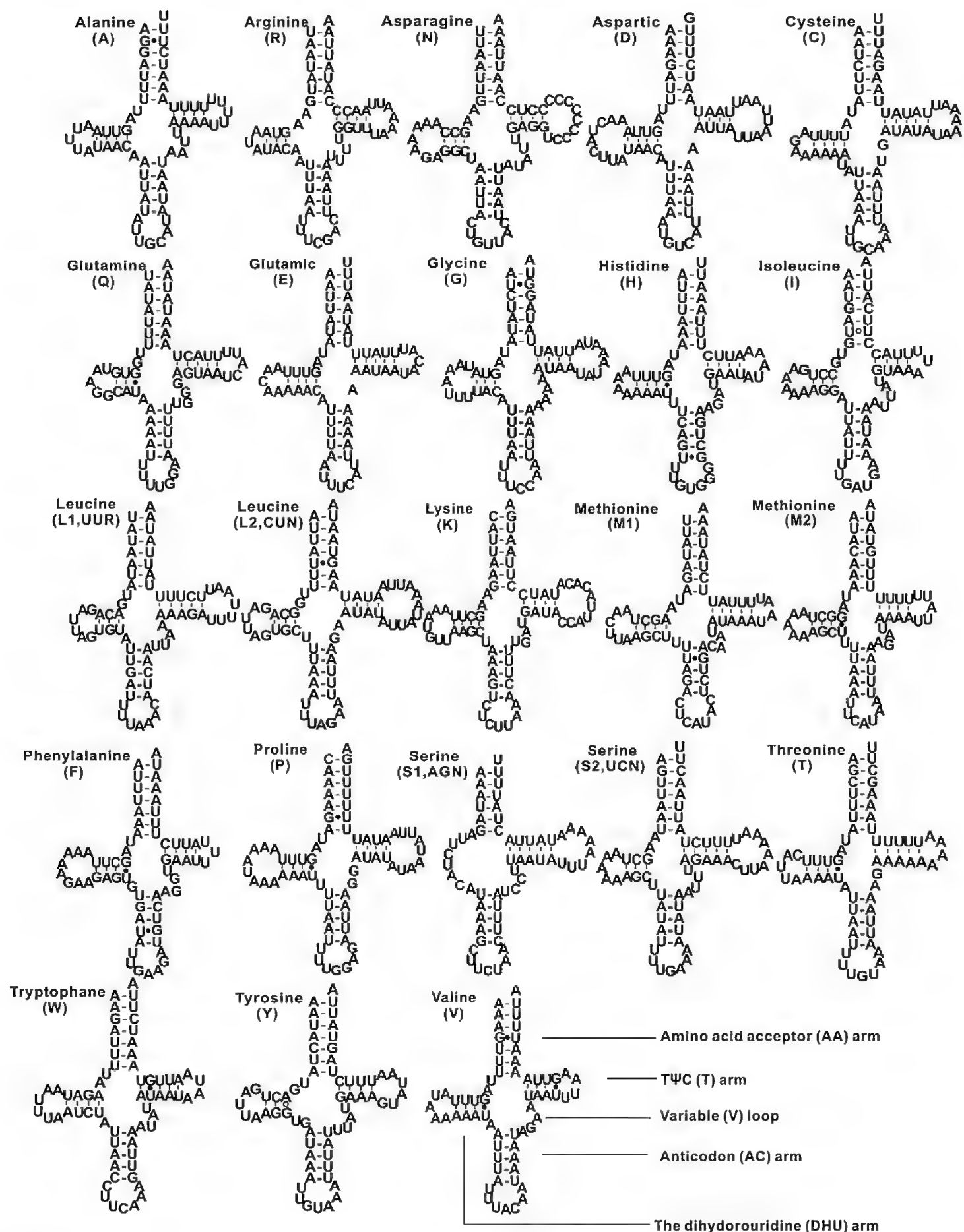


Figure 5. Secondary structures of 23 tRNAs of *O. a. aterrimus* mitochondrial genome. Watson-Crick bonds are showed by dashes, GU pairs by filled dots, and AG and UU by open dots.

study, Eumeninae is the sister group with (Polistinae + Vespinae), which is different from morphological classification “(Eumeninae + (Stenogastrinae + (Vespinae + Polistinae)))” (Carpenter 1982, 2003). So far, there is no reported mitogenome in the subfamily Stenogastrinae, so the relationships among the four subfamilies

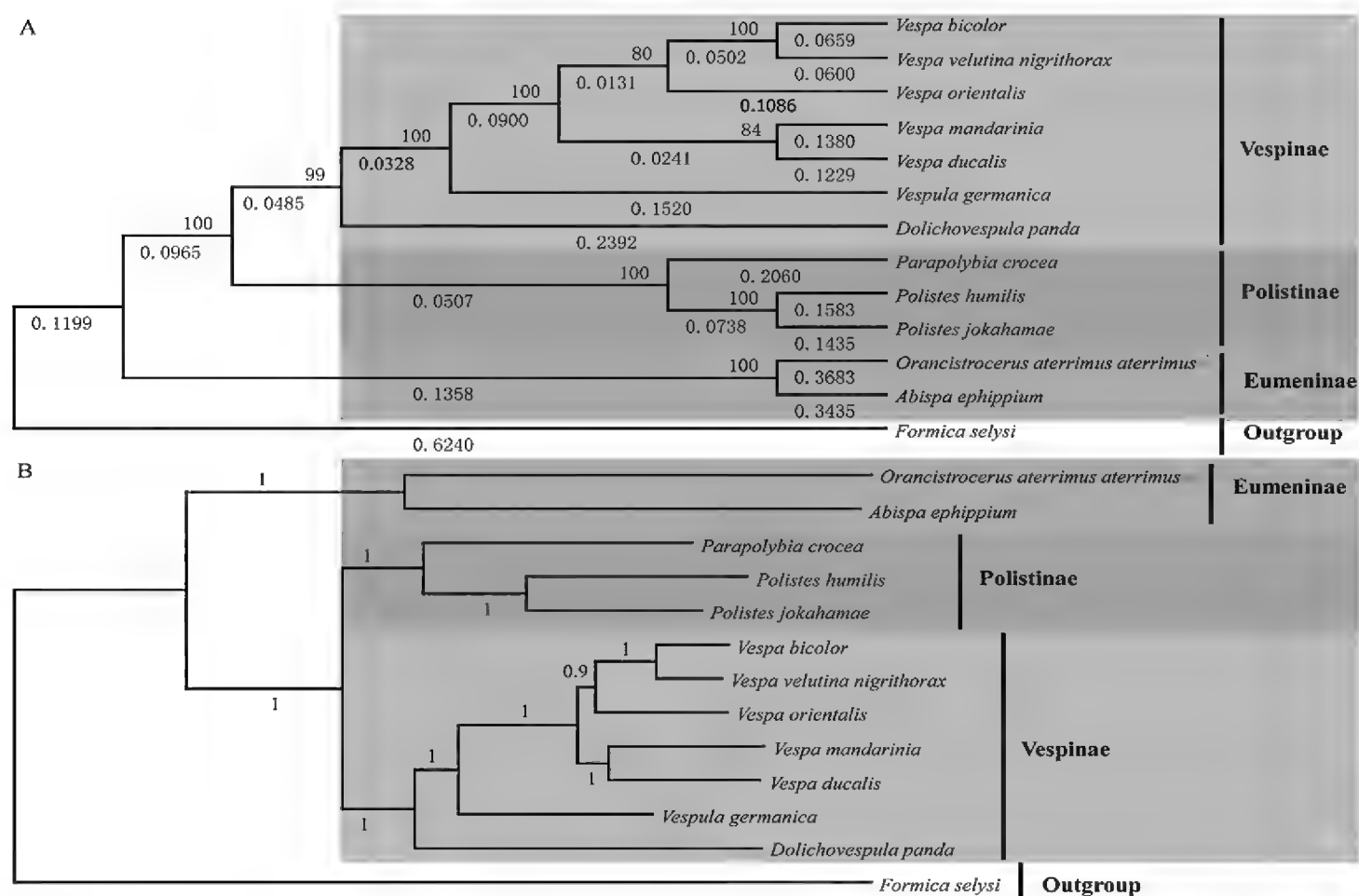


Figure 6. The phylogenetic relationships were established by the 13 PCGs using ML (A) and BI (B) methods. Numbers abutting branches were bootstrap percentages with 1000 replicates (A) and Bayesian posterior probabilities (B). Red pentagram refers to the mitogenome sequences of *O. a. aterrimus*.

Eumeninae, Stenogastrinae, Vespinae and Polistinae based on mitogenomes need to be further explored in our follow-up studies.

Conclusions

According to nine complete mitogenomes reported in the family Vespidae, gene numbers of two species (38 and 41 genes) of the subfamily Eumeninae are more than those of the other seven species (34 - 37 genes) of both Polistinae and Vespinae. The rearrangements of tRNAs are common in Vespidae, but rearrangement rules are different in different subfamilies. The translocation between trnS1 and trnE only happens in the subfamily Vespinae, and there are the same rearrangements in these four complete mitogenomes of *Vespa mandarinia*, *V. ducalis*, *V. orientalis*, and *V. velutina nigrithorax*. The translocation of trnY occurs in both Vespinae and Polistinae, whereas trnY location in Eumeninae is consistent with that of the sawfly *Perga condei*. The number of absent codons in Eumeninae is less than Vespinae and Polistinae. The phylogenetic results of mitogenomes show that *O. a. aterrimus* and *Abispa ephippium* belong to Eumeninae and (Polistinae + Vespinae) and Eumeninae constitute a sister group. Lastly, these results of this study might suggest that Eumeninae derived earlier than both Polistinae and Vespinae, which is consistent with reported research based on morphology.

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